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Mitigating the anthropogenic global warming in the electric power industry

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ABSTRACT

One of the most current and widely discussed factors that could lead to the ultimate end of man's existence and the world at large is global warming. Global warming, described as the greatest environmental challenge in the 21st century, is the increase in the average global air temperature near the surface of the Earth, caused by the gases that trap heat in the atmosphere called greenhouse gases (GHGs). These gases are emitted to the atmosphere mostly as a result of human activities, and can lead to global climate change. The economic losses arising from climate change presently valued at $125 billion annually, has been projected to increase to $600 billion per year by 2030, unless critical measures are taken to reduce the spate of GHG emissions. Globally, the power generation sector is responsible for the largest share of GHG emissions today. The reason for this is that most power plants worldwide still feed on fossil fuels, mostly coal and consequently produce the largest amount of CO_2 emitted into the atmosphere. Mitigating CO_2 emissions in the power industry therefore, would significantly contribute to the global efforts to control GHGs. This paper gives a brief overview of GHGs, discusses the factors that aid global warming, and examines the expected devastating effects of this fundamental global threat on the entire planet. The study further identifies the key areas to mitigate global warming with a particular focus on the electric power industry.

Contents

Abbreviations: CCS, carbon capture and storage; GHG, greenhouse gas; Gt, gigatons; GWP, global warming potential; $MtCO_2$, metric tons of carbon dioxide; IEA, International Energy Administration; IPCC, Intergovernmental Panel on Climate Change; UNFCCC, United Nations Framework Convention on Climate Change.

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1. Introduction

One of the most current and widely discussed factors that could lead to the ultimate end of man's existence and the world at large is global warming. Global warming, also known as the "greenhouse effect", described by the former U.S. Vice President, Albert Gore, as the greatest environmental challenge in the 21st century, is the increase in the average measured global air temperature near the Earth's surface. It is caused by certain gases called greenhouse gases (GHGs) that trap heat in the atmosphere. A prolonged global warming would lead to global climate change. Global warming is divided into natural and anthropogenic types. The former is desirable while the latter should be combated.

Climate change refers to any significant change in measures of climate such as temperature, rainfall, or wind, lasting for a prolonged period of time, usually decades. Naturally, climate change is caused by the solar energy absorbed by the Earth, which also radiates part of the energy back to the space. However, the GHGs present in the atmosphere absorb the energy and again radiate a larger proportion of this energy back to Earth's surface; hence making our planet warmer. In any case, this natural global warming is essential since no life would have survived on the planet Earth with about $-6\,^{\circ}$C. This natural phenomenon has been able to raise the Earth's surface temperature by $20\,^{\circ}$C above what it would have been [1], bringing the average surface temperature to about $14\,^{\circ}$C. The major GHGs in the atmosphere are water vapour, which causes about 36–70 percent of global warming; carbon dioxide (CO_2) causes 9–26 percent; methane (CH_4) causes 4–9 percent; and ozone, which causes 3–7 percent.

On the other hand, anthropogenic global warming is the result of climate change due to emissions of a substantial amount of GHGs into the atmosphere via human activities. In other words, it is man-made global warming, and it is this type that has adverse effects on the universe. It is established scientifically that, since the industrial revolution, there has been an increase in the concentration of various greenhouse gases, leading to increased radiative forcing from CO_2, methane, tropospheric ozone, CFCs and nitrous oxide. For example, the atmospheric concentrations of CO_2 and CH_4 have been found to increase by 31 percent and 149 percent, respectively, since the beginning of the industrial revolution in the mid-1700s [2]. Records have shown that the effect of these GHGs has warmed the planet Earth during the period of between 1906 and 2005, making the average global temperature near the Earth's surface to increase by $0.74 \pm 0.18\,^{\circ}$C [3]. The global mean surface temperature recorded by NASA between 1880 and 2007, which shows an increasing trend, is presented in Fig. 1.

The Intergovernmental Panel on Climate Change (IPCC) concludes that most of the observed increase in globally averaged temperature is most likely to be as a result of the observed increase in the anthropogenic GHGs concentrations. These gases—majorly CO_2 and methane (CH_4) are emitted into the atmosphere in the process of burning fossil fuels for energy. The addition of these gases is seriously enhancing the natural global warming. Meanwhile, climate model projections summarised by the IPCC indicate a further rise in the average global temperature of between 1.1 and $6.4\,^{\circ}$C by the end the 21st century, when compared to 1980–1999 [3]. This range of values results from the use of differing scenarios of future GHG emissions as well as models with differing climate sensitivity.

In combating global warming, many efforts are being made by various nations to ameliorate this problem. One of such efforts is the Kyoto Protocol that has been made between various nations to reduce the emissions of various GHGs. Presently; the Protocol has covered more than 160 countries globally. Many non-profit organisations are also working for the cause. The former U.S. Vice President, Al Gore was one of the foremost U.S. politicians to raise an alarm on the hazards of global warming. He had given various speeches to raise awareness and warned people about the ill effects of global warming. Also, the Stern Review, commissioned in July 2005 and led by Sir Nicholas Stern, has warned of the global

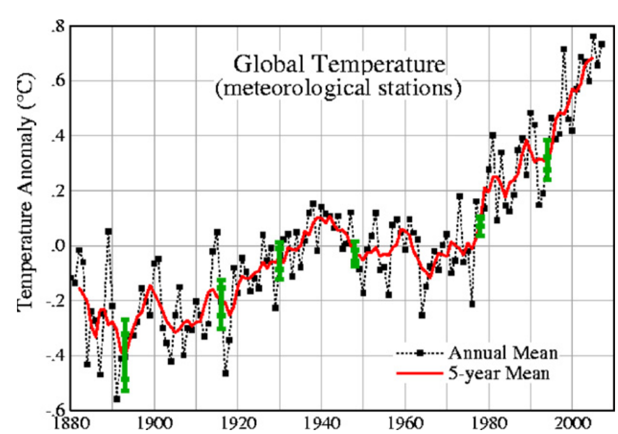

Fig. 1. Global mean surface temperature between 1880 and 2007.

Table 1
The main greenhouse gases.

GHG name	Pre-industrial concentration (ppmv)	Concentration in 1998 (ppmv)	Atmospheric lifetime (years)	Main human activity source	GWP
Water vapour	1–3	1–3	A few days	–	–
Carbon dioxide (CO_2)	280	365	Variable	Fossil fuels, cement production, land-use change	1
Methane (CH_4)	0.7	1.75	12	Fossil fuels, rice paddies waste dumps, livestock	23
Nitrous oxide (N_2O)	0.27	0.31	114	Fertilizers, combustion, industrial processes	296
HFC 23 (CHF_3)	0	1.4×10^{-5}	260	Electronics, refrigerants	12,000
HFC 134a (CF_3CH_2F)	0	7.5×10^{-6}	13.8	Refrigerants	1300
HFC 152a (CH_3CHF_2)	0	5.0×10^{-7}	1.4	Industrial processes	120
Perfluoromethane (CF_4)	4×10^{-5}	8.0×10^{-5}	>50,000	Aluminium production	5700
Perfluoroethane (C_2F_6)	0	3.0×10^{-6}	10,000	Aluminium production	11,900
Sulphur hexafluoride (SF_6)	0	4.2×10^{-6}	3,200	Dielectric fluid	22,200

economic consequences of failing to take a proactive action on climate change [4]. In the same vein, the IPCC's working group III is saddled with the responsibility of crafting reports found to be dealing with mitigation of global warming, and analyzing the cost and benefits of various approaches that could be employed. After 6 years of rigorous study, the IPCC published a report in 2007, comprising the research works of more than 2500 climate scientists/researchers from more than 130 countries. According to the report, global warming is caused mainly by human activities, particularly after the industrial revolution (1750s).

The most notorious emitters of these GHGs are the fossil fuels-fired conventional power plants used for production of electricity. The need for electric energy can never be over-emphasized in the contemporary world. Electricity plays a pivotal role in modern economies, as it is crucial for lighting and the generation of mechanical energy by electric motors used in the industries. In 2008, 78 percent of the world primary energy demand was met by fossil fuels alone [5], and their use is expected to grow in absolute terms over the next 20–30 years in the event that this trend continues [6]. Of this amount, fossil fuels accounted for 69 percent of the total global electricity produced in the same year. Therefore one of the key sectors for feasible and effective GHG control in future is electric power industry, since these emissions are easier to track and control from a limited number of large centralised and stationary power stations, compared to millions of small/mobile emissions sources such as vehicles, small boilers, etc. [3,7,8].

Generally speaking, burning of fossil fuels create two effects in our environment. It produces GHG emissions that cause global warming, and the by-products of burning, such as sulphur dioxide, soot, and ash, which cause global dimming by changing the properties of the clouds. Global dimming is the gradual reduction in the amount of global direct irradiance at the Earth's surface, observed for several decades after the start of systematic measurements in the 1950s [9]. The latter is considered to be outside the scope of this study.

Renewable energy can play a key role in creating a clean, reliable energy future. Using renewable energy produces immediate environmental, as well as other benefits. Recently, distributed generation technologies have received much attention for the potential energy savings and reliability assurances that might be achieved as a result of their widespread adoption. Fuelling the attention, among other factors, have been the possibilities of international agreements to reduce GHG emissions. Other mitigation solutions proposed in this paper include carbon capture and storage, decarbonisation of fossil fuels, increases in the use of nuclear power, improvements in the energy efficiency, etc. The rest of this paper is structured as follows: Section 2 is devoted to a brief description of greenhouse gases, while Section 3 discusses some factors enhancing global warming. A few devastating effects of the global threat are highlighted and discussed in Section 4, whereas Section 5 examines the power sector's share of CO_2 emissions with relevant statistics vis-a-vis other economic sectors. In Section 6, a few mitigation areas are identified and extensively discussed in combating global warming in the realm of power generation. The conclusion to the paper is drawn in Section 7.

2. Greenhouse gases overview

Gases in the atmosphere that trap heat, i.e. prevent heat from escaping to the space, are often called greenhouse gases (GHGs). Naturally, some of these gases, for example CO_2, water vapour, methane, and nitrous oxide are emitted in small fractions into the air through natural processes, such as photosynthesis, etc., while others (like the gases used for aerosols) are exclusively due to human activities. The basic principle of global warming could be explained by considering the radiation energy from the sun that warms the Earth's surface and the thermal energy that is radiated out to space from the Earth and the atmosphere. The GHGs present in the atmosphere absorb the infrared radiation emitted by the Earth's surface and trap the heat to form a blanket over the surface [1] (see Fig. 2). If the amount of energy sent from the sun to the Earth's surface over time, balances the amount of energy radiated back into space, then the temperature of the Earth's surface becomes roughly constant.

The principal GHGs that are emitted into the atmosphere as a result of human activities are CO_2, methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. Table 1 is presented to show the pre-industrial and 1998 concentrations, the atmospheric lifetime, the major human activities, and the global warming potentials of these gases. From the table, it is clear that water vapour is not affected by human activities, whereas CO_2, whose concentration was 280 ppmv in the pre-industrial period (1750–1800) [10] has increased by 30.5 percent in 1998. The other two gases that have significant increase in concentrations as a result of human activities from the table are methane and nitrous oxide. While the former's

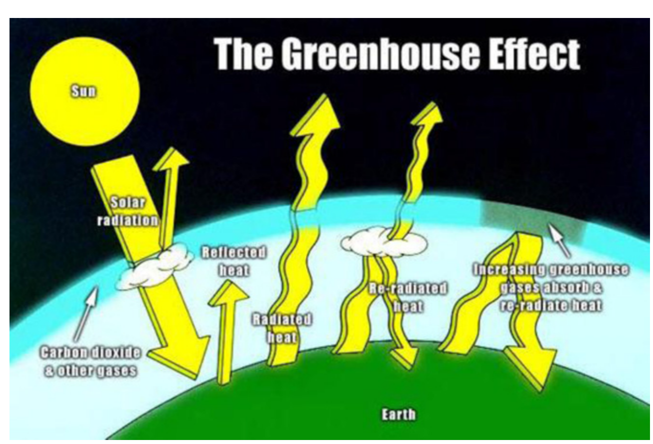

Fig. 2. The greenhouse effect.
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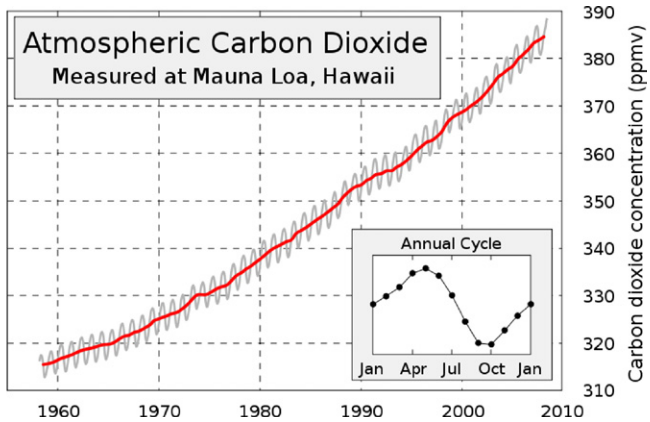


Fig. 3. Mauna Loa measured atmospheric CO_2.

concentrations increased by 150 percent, the latter is 15 percent greater in 1998 than in the pre-industrial era.

2.1. Global warming potential

Global warming potential (GWP) is a quantified measure used within the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) for weighting the climatic impact of emissions of different GHGs [11,12]. Its value is used to compare the abilities of different GHGs to trap heat in the atmosphere. GWPs are based on the heat-absorbing ability of each gas relative to that of CO_2, as well as the amount of the gas removed from the atmosphere over a given number of years, called the gas decay rate. They are also used to define the impact GHGs will have on global warming over different time periods or time horizons, which are usually 20 years, 100 years and 500 years. For most GHGs, the GWP declines as the time horizon increases. This is because the GHG is gradually removed from the atmosphere through natural removal mechanisms, and its influence on the greenhouse effect declines. Some of the CFCs, however, have long atmospheric lifetimes.

By assigning a GWP value to a GHG, it allows policy makers to compare the impacts of emissions and reductions of different gases. For instance, methane is a significant contributor to the greenhouse effect and has a GWP of 23. This means that methane is approximately 23 times more heat-absorptive than CO_2 per unit of weight. Looking at Table 1, it is seen that nitrous oxide is 296 times more heat-absorptive than carbon dioxide, and can linger in the atmosphere for over a hundred years.

2.2. Carbon dioxide

Carbon dioxide (CO_2) enters the atmosphere through the burning of fossil fuels, such as coal, oil, natural gas, solid wastes, trees and wood products. Other notorious sources of this gas into the atmosphere are via chemical reactions, e.g. manufacture of cement, and land use change. Studies reveal that CO_2 alone is responsible for about 70 percent of the GHG warming [13], and approximately 80 percent of atmospheric CO_2 increases are due to use of fossil fuels [14]. Scientists believe that only a little bit above 50 percent of CO_2 being emitted each year is absorbed by trees and the oceans, while the rest remains in the atmosphere. As concentrations of CO_2 in the air increase, so does the temperature. This assertion is glaringly evident in Fig. 1 relative to Fig. 3 between 1958 and 2007. Since CO_2 plays a key role in Earth's climate [15], it can be concluded that, research on CO_2 is often closely linked with research on climate change.

Concentrations of future CO_2 are expected to rise dramatically, as projected in Mauna Loa Observatory in Hawaii as shown in Fig. 3, due to the ongoing burning of fossil fuels and land-use change. Even if emissions of CO_2 stay the same as they are now, concentrations of atmospheric CO_2 will increase to 700 parts per million by volume (ppmv) by 2100 [16]. As a result, this is anticipated to raise the mean global temperatures by about 1.9 °C over the next 100 years.

2.3. Water vapour

Water vapour constitutes Earth's most significant greenhouse gas, accounting for about 95 percent of Earth's greenhouse effect. Interestingly, many 'facts and figures' regarding global warming completely ignore the powerful effects of this gas in the greenhouse system, overstating human impacts as much as 20-fold. Although water vapour traps more heat than CO_2, because of the relationships among CO_2, water vapour and climate, to combat global warming, all nations must focus on controlling CO_2, most especially when water vapour occurs 100 percent naturally, and not as a result of human activities, as portrayed in Table 1.

2.4. Methane

Methane is emitted in the course of production and transportation of coal, natural gas, and oil. Other sources of methane include emissions from livestock, decay of organic solid wastes, and from agricultural activities. Molecule for molecule, methane is a more potent GHG than CO_2, but its concentration is much smaller, as could be seen in Table 1, which makes its overall radiative forcing to be about one-fourth of that from CO_2. The most promising and cost-effective way to reduce methane emissions from cattle is to improve the efficiency of livestock production by improving feed quality, livestock management and genetic potential, especially in developing countries [17]. Methane production can be reduced in this sector by feeding high-protein/low-fiber rations, specifically by feeding more concentrates [18].

2.5. Nitrogen oxides

NOx is a generic term for various oxides of nitrogen. They are produced and emitted into the atmosphere during agricultural and industrial activities. Nitrous oxide is also produced in the combustion of fossil fuels and solid waste. They are believed to worsen asthmatic conditions, react with the oxygen in the air to produce ozone, which forms nitric acid when dissolved in water. Nitrogen oxides dissolved in the atmospheric moisture, result in acid rain, which could be a serious environmental problem, as acidification of Scandinavian lakes in the 1970s is a case of reference [19].

2.6. Halocarbons, perfluorocarbons, and sulphur hexafluoride

Halocarbons, perfluorocarbons, and sulphur hexafluoride are synthetic, powerful GHGs that are produced from a number of industrial processes. Fluorinated gases are sometimes called ozone depleting substances, e.g. CFCs, HCFCs, and halons. These gases are actually emitted in small quantities but due to their potency, they are referred to as high global warming potential gases (see Table 1). They cause depletion of the ozone layer that protects life on Earth from the intense and harmful ultraviolet (UV) rays; consequently allowing more UV radiation to reach the ground, leading to more cases of cataracts, skin cancer, and other health and environmental problems [20].

3. Factors enhancing global warming

3.1. Fossil fuels burning

Fossil fuels, which contain high percentages of carbon, are formed by natural resources such as anaerobic decomposition of buried dead organisms. They are considered as non-renewable resources because they take millions of years to form, and reserves are being depleted at a faster rate than new ones are being made. The 2007 report of the U.S. Energy Information Administration shows that the primary energy sources in the year consisted of 36 percent of petroleum, 27.4 percent of coal, and 23.0 percent of natural gas. These put together accounted for 86.4 percent share for fossil fuels in primary energy consumption in the world. The carbon locked in these fuels is released to the air in form of CO_2 in the process of burning them as fuel to produce electrical energy to power the engines and economies of modern society. According to the U.S. Department of Energy on greenhouse gases, the burning of fossil fuels produces around 21.3 billion tons of CO_2 per year. Of this amount, it is estimated that only about 50 percent is absorbed by natural processes, thus leaving a net increase of 10.65 billion tons of atmospheric CO_2 annually, thus warming the biosphere more.

3.2. Land-use change

CO_2 is emitted into the atmosphere as a result of man-made land use changes. For example, millions of acres of rain forest are destroyed annually for one purpose or another. Other factors include shifting cultivation, vegetation re-growth on abandoned croplands and pastures. As well, natural vegetation is replaced with asphalt or concrete, which substantially alter the way the Earth's surface reflects sunlight and releases thermal energy. All these changes affect regional evaporation, runoff and rainfall patterns, which in turn facilitate global warming a great deal. To restore the imbalance, the following options are recommended [3]:

- maintaining or increasing the forest area;
- maintaining or increasing the site-level carbon density;
- maintaining or increasing the landscape-level carbon density;
- increasing off-site carbon stocks in wood products and enhancing product and fuel substitution.

3.3. Population growth

Another factor leading to global warming is population density. No doubt, there is a clear relationship between population growth and the problem of global warming. Currently there are too many people in the world using all sorts of technologies that are not environmentally friendly. As of January 2011, the real time world population was estimated at 6.89 billion [21]. Based on the U. S. Census Bureau, this figure is expected to reach 9 billion by 2044–an increase of 50 percent that requires only 45 years, from 1999 of 6 billion [22]. Consequently, this ever-increasing world population would translate to a higher demand for electric energy for day-to-day activities. The data obtained from the International Data Base for the world population from 1950 projected to 2050 is plotted and presented in Fig. 4. It is shown in the figure that the population is expected to hit 8.55 billion by year 2035, which would certainly translate to more energy demand and consequently, more GHG emissions.

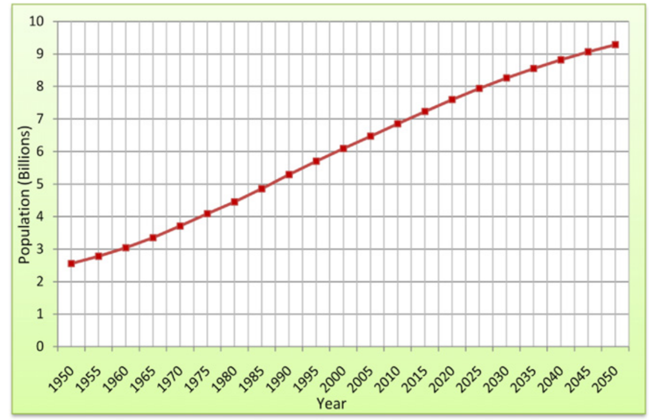


Fig. 4. World population growth history and projections.

4. Devastating effects of global warming

4.1. Higher evaporation rate

One of the most feedback effects of global warming relates to evaporation of water into the atmosphere. This makes the atmosphere to warm further since water vapour itself also acts as greenhouse gas. When global temperature increases, ice near the poles melts at a fast rate; thus making land or open water to take the place of the ice as it melts. Since land and open water are less reflective than the melted ice, both absorb more solar radiation, which in turn causes more warming and ice melting, and the cycle continues. This often results in an unbalanced distribution of global rainfall and thus may bring more dry spells and floods, simultaneously in different parts of the world. The recent frequent drought in the north and floods in the south of China could be used to reinforce this conclusion; just as Eastern Australia simultaneously experienced two extreme weather conditions in 2009.

4.2. Spread of disease and higher health risks

Studies have revealed that global warming is creating conducive conditions for the spread of certain infectious diseases, thereby subjecting human health to grave risks. The most likely vector borne diseases caused by this global threat include malaria, dengue fever, encephalitis and many other diseases associated with mosquitoes and rodents [23]. Similarly, scientists have affirmed that rise in air temperatures tend to intensify the concentration of ozone layer in the Earth atmosphere. It is common knowledge that the natural layer of ozone in the upper atmosphere prevents penetration of harmful ultraviolet radiation from reaching the lower levels. If ozone at ground level is damaged, then it can impair the lung tissue and cause respiratory problems like chronic asthma and bronchitis. Even marginal damage to ozone can cause chest pain, severe infections in lungs, nausea and other respiratory diseases.

Similarly, based on the World Health Organisation's estimates, between 12 and 15 million people worldwide become blind from cataracts annually, of which up to 20 percent may be caused/enhanced by sun exposure. Furthermore, a growing body of evidence suggests that environmental levels of UV radiation may suppress cell-mediated immunity and thereby enhance the risk of infectious diseases and limit the efficacy of vaccinations [24]. Skin cancer is another deadly disease caused by exposure to high UV radiations. Records show that over 65,000 cases of skin cancer were reported in 1999 in UK. The number of skin cancer cases has more than doubled since the early 1980s. Over 2000 people die from skin cancer each year [24]. Both of these aggravate the health conditions of poor and vulnerable groups, especially children of the developing

world. Incidentally, many developing countries are located close to the equator and hence, people are exposed to the very high levels of UV radiation that occur in these regions.

4.3. Rises in global sea levels

Two factors are responsible for rising sea levels. The first one is the extra water produced from ice melts, while the other factor is the natural expansion of water as it becomes warmer. The range of sea ice at both poles continues to shrink as it melts. Scientists have estimated that a sea rise of only 50 centimetres would increase the number of people that live in areas at risk of flooding from 48 million of 1998 to 92 million, and that 118 million people would be affected with a sea level rise of 1 m. Judging by the level of GHGs present in the atmosphere today, scientists believe that the Earth may warm enough to totally melt the sea ice located in the poles, which may result in a global sea level rise of 50 cm over the next 40–100 years [25].

Diverse damage from rising seas include flooding of the cities in the coastal areas of the world, increase in the intensity of hurricanes by more than 50 percent, a hurricane Andrew's devastation in 1992 has set a record, wetlands are lost as sea levels rise, threat of salt water intruding into underground fresh water reserves in coastal areas, etc. This is corroborated by a United Nation's report published in 1992 that proposes the flooding of the coastal plains of Bangladesh and the Netherlands by the year 2100, if CO_2 and other GHGs emissions should continue with its trend.

4.4. Plant and animal species extinction

Extinction of animal and plant species presents a picture analogous to that of sea level. Extinctions are already occurring as a result of various stresses, mostly human-made, including climate change. Plant and animal distributions are a reflection of the regional climates to which they are adapted. Thus, plants and animals attempt to migrate in response to climate change, but their paths may be blocked by human-constructed obstacles or natural barriers such as coastlines. Based on the future climate predictions, a study has suggested that between 18 percent and 35 percent of a sample of 1103 animals and plant species are likely to be extinct by 2050 [26].

4.5. Reduction in crop yields

According to David Battisti, a climatologist at the University of Washington, "there is a 90 percent chance that average temperatures in the tropics and subtropics will be higher than the hottest heat waves of the past century". This would cause a reduction in the water available for irrigation purposes, and consequently a drop in crop yields, as a result of changes in winds and ocean currents, precipitation and water resources [14]. Lots of research works have been carried out by experts to assess the impacts of global warming on crop yields. Results from these studies indicate that increased moisture stress due to warmer and drier conditions, as a consequence of this global environmental threat, could reduce the yields of current varieties of major crops in many regions of the world [27].

4.6. Economic consequences

According to a report in 2009 [28], more than 3 billion people living in desert regions, most of whom rely heavily on locally produced crops for both food and income would be affected as a result of global warming. The choice for these people would be either to migrate to a milder clime or remain there and go hungry as a result of climate change within the next 100 years. Migration obviously has some economic implications. Another report

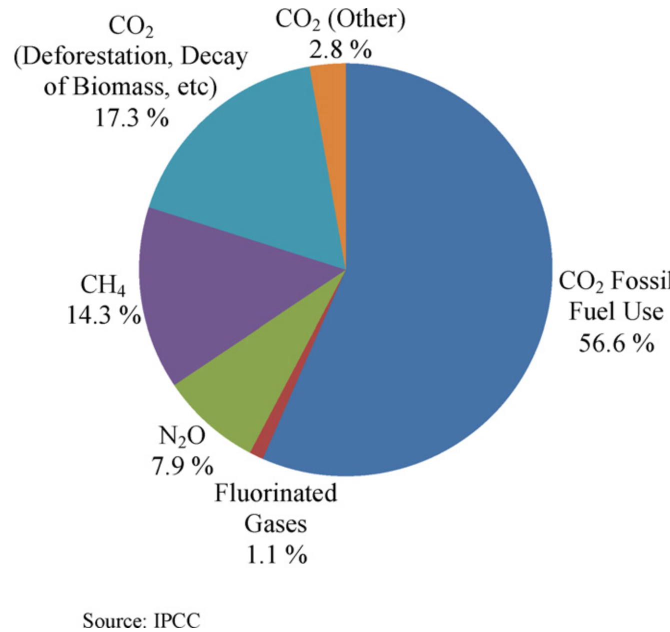


Fig. 5. Global GHGs emissions in 2004.

says that if emissions are not brought under control within 25 years, 310 million more people will suffer adverse health consequences related to temperature increases, 20 million more people will fall into poverty, and 75 million extra people will be displaced by climate change. Presently, economic losses arising from climate change is estimated at $125 billion annually. This amount would rise to $600 billion per year by 2030 unless GHG emissions are severely reduced [29].

5. Power industry's share of CO_2 emissions

To identify the most productive mitigation strategies, it is crucial to understand the current as well as the projected sources of GHGs, most especially CO_2 [30]. Looking at Fig. 5, it is glaringly evident that CO_2 constitutes the largest share (76.7 percent) of the total global GHGs emissions recorded in 2004. In the same vein, energy supply sector which comprises of power generation and heat supply, accounted for nearly 26 percent of the overall anthropogenic GHG emissions in the same year, as depicted in Fig. 6.

To narrow down to CO_2 emissions, Fig. 7 identifies individual contribution of each sector to global CO_2 emissions. As a group, energy supply, which is responsible for 41 percent of the total global CO_2 is by far the largest producer of CO_2 in 2008, followed by the transportation sector. In fact, it is glaringly visible in the figure that these two sectors alone constitute two-thirds of the total CO_2 in the atmosphere in the year. According to the International Energy Agency, out of the 41 percent of the man-made CO_2 emissions mentioned previously, the power sector is responsible for 37 percent. The sector creates about 23 billion tons of global CO_2 emissions per year. Out of this, the United States produces the most CO_2 from electricity generation, releasing 2.8 billion tons of CO_2 each year, while China is close to overtaking it with her annual 2.7 billion tons emissions [31]. By this amount, China CO_2 emissions in electric supply sector is about half of the country's total volume, even though plans are still underway to expand her coal-fired facilities in the next decade [8]. In the UK, 38 percent of GHG emissions produced is from energy supply sector [32].

Carbon dioxide emissions by source compiled in 2005 by Information Analysis Center, World Resources Institute (WRI) for the year 2000 is plotted and shown in Fig. 8. The emissions sources

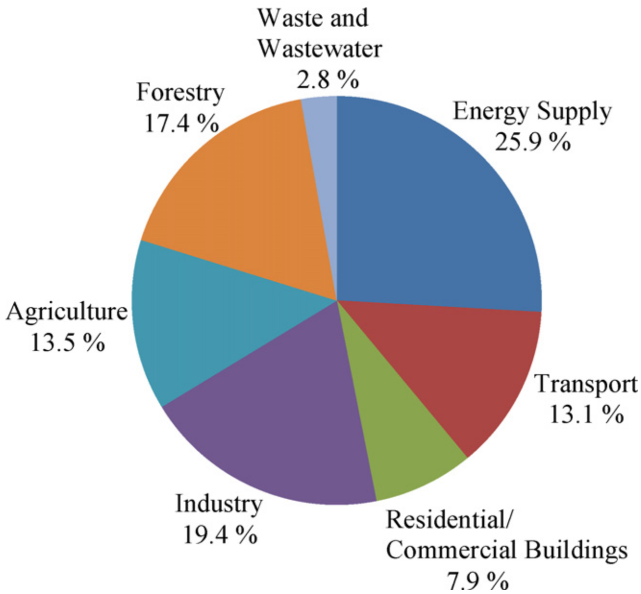


Fig. 6. Global GHGs emissions by economic sector in 2004.

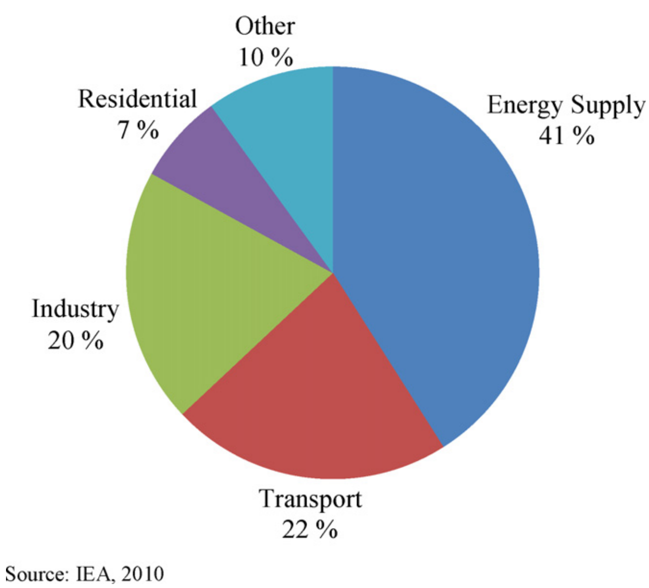


Fig. 7. World CO_2 emissions by sector in 2008.

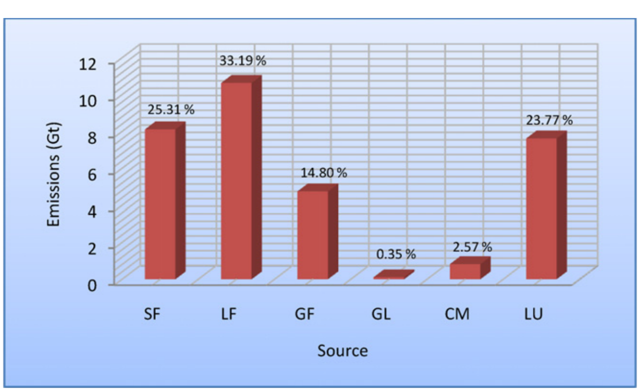


Fig. 8. Global CO_2 emissions by source in year 2000.

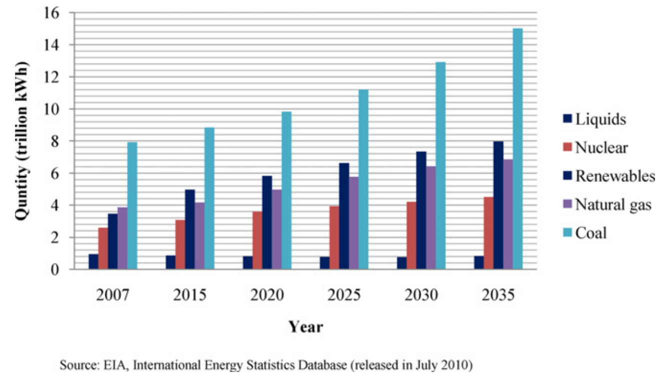


Fig. 9. World net electricity generation by fuel.

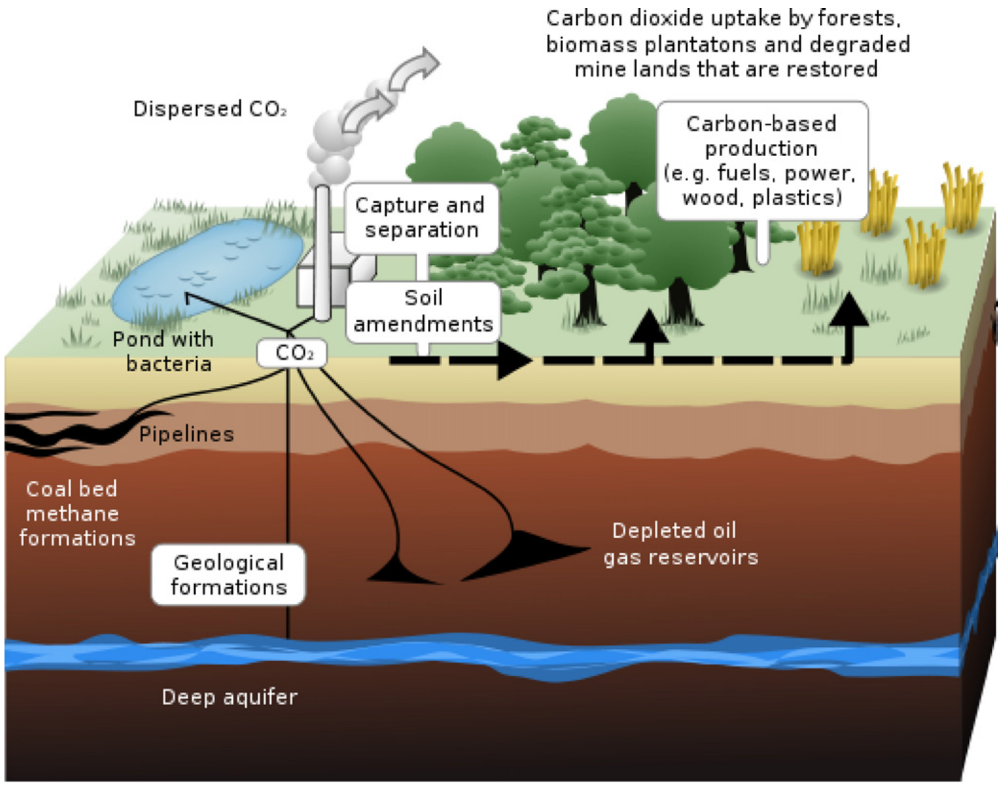
considered are CO_2 emitted primarily in to the air from burning of solid fuels (SF) such as coal, liquid fuels (LF) such as petroleum products, gaseous fuels (GF), e.g. natural gas, gas flaring (GL), cement manufacturing (CM), and land-use change (LU). All together, it is evident from the plots that 73.3 percent of the total anthropogenic CO_2 emissions in the atmosphere is from fossil fuels burning.

Meanwhile, the International Energy Outlook (IEO2010) [33] has forecasted the world energy demand at 739 quadrillion Btu in 2035. This figure is equivalent to 49 percent increase of the energy consumed in 2007, estimated at 495 quadrillion Btu. To adequately cope with the projected demand, the said document similarly projected a growth in the generation of 95.12 MWh in the same period. Fig. 9 illustrates the energy mix of the projected generation from 2007 to 2035.

From the figure, it is seen that the world net coal-fired generation nearly doubles over the projection period, from 7.9 trillion kWh in 2007 to 15.0 trillion kWh in 2035. It is apparent in the reference case that coal continues to fuel the largest share of worldwide electric power production by a wide margin of 43 percent of the total generation. With this scenario, all things being equal, more GHGs are expected to be emitted into the atmosphere, leading to more global warming. Due to this fact, the power generation sector, which is projected to grow at an annual rate of 2 percent, is seen to have the greatest potential to reduce CO_2 emissions in the coming decades [30]. To accomplish this goal, the CO_2 emissions per kWh of electrical energy produced can be reduced by using newer and novel power production technologies. Current retrofit technology is theoretically available, but will likely be substantially more expensive per unit of power generated, than would be the case for new plants with CO_2 capture [30]. To mitigate global warming arising from the power industry, various areas and approaches are suggested and discussed in details in the following section of this paper.

6. Mitigating global warming in power sector

Since the highest amount of CO_2 is generated in the power sector, curbing the CO_2 produced in this sector would go a long way in mitigating global warming. To address this issue, it is suggested in [4] to decarbonise the power sector by at least 60 percent by 2050 since coal emits about 1.7 times as much carbon per kWh of energy produced as natural gas and 1.25 times as much as oil. However, the task to accomplish this is not an easy one, as elaborated in the later part of this paper. Other measures proposed for addressing global warming in the realm of power generation identified and discussed in this study include adoption of carbon capture and storage technology, improvement in energy efficiency, increasing the use of renewable energy, increasing the share of nuclear power generation, and decarbonisation of fossil fuels. Each of these



Source: http://en.wikipedia.org/wiki/File:Carbon_sequestration-2009-10-07.svg

Fig. 10. Carbon capture and storage facilities.

possible mitigation techniques is discussed in turn in the following subsections.

6.1. Adoption of carbon capture and storage technology

Carbon capture and storage (CCS) is the capture and diversion of CO_2 from large point sources such as power plants and subsequently storing it safely instead of releasing it into the atmosphere. It could be saved in underground geological formations, such as saline aquifers, depleted oil and gas fields, unminable coal seams, deep ocean, or as carbonate minerals [34], as illustrated in Fig. 10. The application of CO_2 capture and subsequent geological storage is a promising option to significantly reduce the GHG emissions of coal-fired power plants.

The CCS technology has three components, namely *capture*, *transportation* and *long-term storage*. Capture is defined as the physical removal of carbon dioxide that would have otherwise been emitted into the atmosphere. For coal-fired power plants, the process of CO_2 capture could be accomplished in three different ways: (i) post-combustion capture, i.e. separation of CO_2 from the flue gas of the power plant, (ii) pre-combustion capture, which involves gasifying the coal and removing CO_2 before combustion takes place, and (iii) oxy-combustion process, where combustion occurs in a high-oxygen environment, producing a higher concentration of CO_2 in the waste stream to ease carbon capture process [33]. Separation technologies for post-combustion capture of CO_2 from fossil-fired power plants include absorption, adsorption, and membrane processes [35–38]. Post-combustion capture technology promises to cut roughly 85 percent of CO_2 emissions from coal-fired power plants, thus ensuring their viability in the longer term, and can also be easily retrofitted into the existing coal-fired plant infrastructure.

Transportation is required to convey CO_2 from power plant sites to suitable storage locations. Given the quantities of carbon dioxide that are likely to be captured from coal-fired power plants, pipelines have been suggested the most likely mode for transporting the captured gas to geologic sequestration sites. Long-term storage requires permanent sequestration of CO_2 to prevent the captured emissions from entering the atmosphere. The ability to handle large amounts of CO_2 injections depends on the geologic characteristics of a particular site, such as the depth, thickness, and permeability of a given formation. Currently, deep saline aquifers and depleted oil and gas fields are seen as the most likely candidates for long-term storage. Other types of geological formations are currently under investigation, in the meantime [33].

Widespread deployment of CCS would facilitate the use of coal in the presence of GHG policies aimed at reducing CO_2 emissions. Without CCS, reducing CO_2 emissions probably would require a significant curtailment of global coal use, which is not presently feasible given the fact that it remains the world's most widely available fossil fuel. The IPCC believes that CCS could contribute between 10 percent and 55 percent of the cumulative worldwide carbon-mitigation effort over the next 90 years. The Agency states that CCS is "the most important single new technology for CO_2 savings" in power generation and industry sectors [39]. Although up to 40 percent additional energy is required to run a CCS coal power plant relative to a conventional coal plant, one good thing is that CCS could potentially capture about 90 percent of all the carbon emitted by the plant, compared to a conventional coal plant without it [39]. Norway, the first country to embark on storing CO_2, has been able to cut her emissions by almost a million tons annually, which is equivalent to about 3 percent of the country's 1990 levels [39].

Fig. 11, the data of which are obtained from [40], shows the mean value life-cycle GHG emissions from the conventional power plants. It could be appreciated from the figure that while lignite and coal-fired power plants produce 1100 and 1000 gCO_2-eq/kWh, respectively, CCS produces only 130 gCO_2-eq per unit of energy generated. In other words, CCS technology with a coal plant would

Table 2
Mean value of life-cycle GHG emissions for selected power plants.

Option	Total emissions avoided in 2030 ($GtCO_2$-eq)
Fuel switching & plant efficiency	1.07
CCS	0.81
Wind	0.93
Nuclear	1.88
Hydro	0.87
Bioenergy	1.22
Geothermal	0.43
PV and CSP	0.25

Source: IEA (2004).

produce just 13 percent of what a conventional coal-fired plant would have generated. As a result of this, 0.81 $GtCO_2$-eq of GHG emissions is projected to be avoided by 2030, as illustrated in Table 2.

However, despite this great achievement, a major concern with CCS is leakage of sequestered CO_2 through the injection pipe. Although the injection pipe is usually protected with non-return valves, which prevents release during power outage, there is still a risk that the pipe itself could tear and leak due to the high pressure. A reference case is the small incident of CO_2 emissions leakage that resulted in the deaths of a small group of ducks in December 2008 at Berkel and Rodenrijs [41]. Other issues surrounding CCS projects include uncertainty about the ultimate cost and feasibility of CCS, identifying the person/body to be responsible for the sequestered CO_2, establishing clear regulatory jurisdiction over pipeline construction, and overcoming potential public opposition to CCS facilities that could be a barrier to widespread deployment of the technology. Due to the aforementioned factors, and the fact that large-scale demonstration projects are expected to be very expensive, the private financial community is likely to consider the initial investments in CCS as risky [33], and thus may not be willing to adopt the option. Adequate incentives, in form of subsidy and favourable government policies, would nevertheless motivate them.

6.2. *Energy efficiency improvement*

Another good way to curb global warming is via efficient use of energy, often simply called *energy efficiency*. Energy efficiency is the goal of efforts to reduce the amount of energy required to provide products and services. Currently lots of energy is used inefficiently, or better put, wasted in many countries. Recent studies have shown that in most developed countries, it is possible to achieve improvements in energy efficiency of 30 percent or more, with a little or no net cost and often with significant overall savings. For example, insulating a home allows a building to use less heating and cooling energy to achieve and maintain a comfortable temperature. Also, it has been confirmed that by installing fluorescent lights or natural skylights, it is possible to reduce the amount of energy required to attain the same level of illumination compared to using traditional incandescent light bulbs, which consume two-thirds more energy [42].

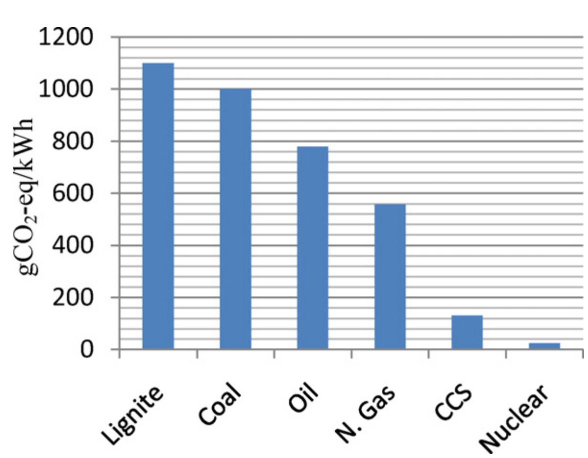


Fig. 11. Mean value of life-cycle GHG emissions for selected power plants.

According to the International Energy Agency, improved energy efficiency in buildings, industrial processes and transportation could reduce the world's energy needs in 2050 by one-third, and help control global GHG emissions [43]. For example, heating and cooling systems of buildings account for 30–50 percent of the global energy consumption, therefore increased efficiency of such systems translates to a considerable reduction in the global energy consumption [44]. This action would consequently result in less energy demand which would in the end have a positive impact on the GHG emissions produced in the process. Demand-side energy efficiency opportunities include improving the energy performance of equipment such as cookstoves, lamps, electric motors, appliances, boilers, buildings, etc., and of processes, particularly in the energy-intensive industries of aluminum, cement, chemicals, fertilizers, iron and steel, etc. In Ref. [45], three approaches are suggested to improve energy efficiency in the industrial sector, which constitutes 37 percent of the world energy consumption. They include energy management, energy savings via application of new technologies and energy savings attained due to good government policies/regulations.

Energy efficiency has proved to be a cost-effective strategy for building economies without necessarily growing energy consumption. For example, the state of California began implementing energy-efficiency measures in the mid-1970s, including building code and appliance standards with strict efficiency requirements. During the following years, California's energy consumption has remained approximately flat on a per capita basis while national U.S. consumption doubled. The International Energy Agency (IEA) is strongly committed to giving the necessary support to energy efficiency in improving energy security, contributing to economic development and mitigating anthropogenic global warming that could result to climate change. In IEA 2009 report, energy efficiency is identified as the single most important component of a low-carbon future, which is believed to be capable of limiting GHG emissions to 450 parts per million (ppm) in the atmosphere. In fact, the scenario shows energy efficiency accounting for two-thirds of reductions in energy-related CO_2 emissions in 2020 and over half in 2030 [46].

Improving energy efficiency will require deployment of new technologies, market mechanisms, such as emissions trading and government policies that can influence the actions of millions of various classes of energy consumers [42]. These efficiency improvements will come from all consuming sectors, including buildings, appliances and equipment, lighting, transport and industry, where it is projected to deliver almost half of the emissions reductions, which translates to about 1.2 gigatons (Gt) [46]. However, certain enabling conditions are required before energy providers would be ready to embrace the role of energy efficiency implementer, which includes the following [47]:

(I) ability to recover programme costs;
(II) compensation of foregone revenues owing to lower sales;
(III) institutional or financial incentives for management and/or shareholders to engage;
(IV) acceptable levels of regulatory and other risk.

To make the achievement of this level of collective action possible, many countries have enacted various energy efficiency laws

and have thus set national defined improvement targets to enable them significantly cut the level of their respective CO_2 emissions. For example, Canada and the United States set a target of reducing CO_2 emissions by 17 percent by 2020 and Canada wishes to go extra mile by 60 percent come 2050 compared with 2005 levels. Similarly, European Union, Germany, Greece, Hungary, Ireland, Italy, Spain and France wish to reduce CO_2 by 20 percent by 2020 when compared to 1990 levels. On the other hand, Mexico sets a reduction of CO_2 emissions by 30 percent below the "business-as-usual" (BAU) scenario by 2020. While South Africa is poised to reducing CO_2 emissions by 34 percent by 2020 and by 42 percent by 2025 below BAU, the United Kingdom has set a mandatory economic-wide target to reduce CO_2 emissions by 34 percent in 2020 compared to a 1990 baseline [46].

6.2.1. Adoption of a more efficient fossil fuels conversion

Weaning humanity completely off fossil fuels might seem realistically impossible, being the world's most widely available fuel at present and even in decades to come. Therefore, one strategy for the control of GHG emissions arising from their combustion is adoption of a more efficient conversion of these fossil fuels. Apparently, typical conversion efficiencies for present day operating systems are in the range of 27–40 percent for lignite fired plants, 30–45 percent for coal, 34–43 percent and 35–55 percent for oil and natural gas-fired plants, respectively [48], with nearly twice the GHG emissions for low efficiency plants compared to efficient ones. In the medium term, conversion efficiencies for best available technologies are expected to be in the range of 50–55 percent for coal, and 60–65 percent for gas-fired plants, thus reducing CO_2 emissions. As an illustration, a 27 percent reduction in CO_2 emissions could be attained by replacing a coal-fired steam turbine, whose efficiency is 35 percent, with a 48 percent efficient plant using advanced steam, pulverised-coal technology, as shown in Table 3. Similarly replacing a 32 percent efficient natural gas single cycle with 50 percent natural gas with combined cycle would avoid 227 gCO_2-eq/kWh, which is equivalent to approximately 36 percent of the total CO_2 emissions from a conventional technology.

Studies have revealed that China, the biggest user of coal for electric power generation in the world, could cut about 20 percent of her coal use should her power plants be as efficient as average power plants in Japan. In the same vein, the biggest world's user of natural gas for electricity generation, Russia, could use only two-third of natural gas if the efficiency of her power plants should have the same average efficiency as Western European gas-fired plants [40]. Although efforts are being made to reduce the share of fossil fuels (coal, gas and oil) from 67.77 percent in 2007 to 64.53 percent projected in 2035, in the global electric power generation based on IEO2010, there is still a need for various nations to formulate policies that would create enabling environment for adoption of highly efficient fossil fuel power plants, to reduce the net global GHG emissions.

6.2.2. Waste heat recovery via CHP systems

Power generation systems produce large amounts of heat in the process of converting fuel into electricity. More than two-thirds of the energy content of the input fuel is converted to heat, and the heat is usually wasted in many conventional central generating plants. As an alternative, an industrial user with significant thermal and power needs can generate both energies in a single combined heat and power (CHP) system located at or near the site of consumption. Most distributed generation technologies considered for the commercial sector provide useful heat as well as electricity, providing the potential for use as CHP systems. The capture and use of heat to satisfy water and space heating needs often make CHP systems more economically attractive than systems that are used exclusively for electricity generation.

Table 4
Number of power project and emissions reduction for 2004.

Mitigation option	No of projects	Emissions reduction ($mMtCO_2$-eq)
Availability improvements	45	93.8
Fuel switching	51	12.0
Low emitting capacity	100	72.7
Efficiency improvements	178	12.8
Cogen and waste heat recovery	18	2.6
High-efficiency transformers	30	2.1
Reconductoring	27	2.0
Distribution voltage upgrades	13	2.8

Because CHP involves recovery and use of thermal energy that would otherwise be wasted, it reduces the amount of fossil fuel that must be burnt to meet the required energy need, thus reducing GHG emissions. In 2004, emissions reduction reported for CHP projects totalled 2.6 million $MtCO_2$-eq, as shown in Table 4. Various topologies for CHP plants are shown and discussed in Ref. [49], where it is found that CHP plants achieved higher emission reductions. Similarly, nine cogeneration projects feeding on bagasse, in contrast to fossil fuels, were used for generation of electricity in some Indian sugar mills. The size of cogeneration plants which ranged from 12 to 24 MW, with a total capacity of 600 MW, helped India to reduce her CO_2 emissions by more than 4 million tons annually [50].

6.2.3. Rehabilitation of power plant and/or network components

Rehabilitating power plants of older vintage and improving their efficiency is thus economically preferable to acquiring sites and constructing new ones. Many developing countries have transmission and distribution losses that exceed 20 percent compared to that of well-managed systems, which incur approximately 6–8 percent power loss [51]. Reducing transmission losses is cost effective and can lead to significant reductions in fuel use and carbon emissions. This could be achieved via the following approaches.

6.2.3.1. Use of high-efficiency transformers. Power transformers that are used for changing the voltage level of one segment of the power network to another are a source of system losses. The loss is due to the impedance offered by the windings to the flow of current as well as eddy currents in steel of the transformer. Losses could be significantly reduced by replacing the existing transformers with high efficiency ones, such as transformers with improved silicon steel and amorphous core transformers [52]. A total number of 30 high-efficiency transformer projects were recorded in 2004, and this was able to avoid 2.1 million $MtCO_2$-eq of GHG emissions, as presented in Table 4.

6.2.3.2. Reconductoring. Similar to transformers, feeders and transmission lines conductors are other sources of losses on power networks. It is common knowledge that smaller diameter conductors offer higher resistance to flow of currents, hence resulting in greater line losses due to heating effects. A reduction in this loss could be achieved by replacing the existing conductors with larger diameter ones. Alternatively, it can be achieved by reducing the resistance of the conductor using superconductive materials, which do not only reduce line losses but also permits increase in transmission capacity of the lines. In 2004, a total of 27 reconductoring projects with emissions reduction of 2.0 million $MtCO_2$-eq were reported (see Table 4).

6.2.3.3. Upgrade of distribution voltage. Another way to reduce line losses is by upgrading the voltage of all segments of the power system. The rationale behind this suggestion is that line losses are partly dependent on the voltage of operation at transmission

Table 3
CO_2 emission reduction by fuel substitution and energy conversion efficiency in electricity generation.

Existing generation technology			Mitigation/substitution option			Emission reduction (gCO_2/kWh)
Energy source	Efficiency (%)	Emission coefficient (gCO_2/kWh)	Switching option	Efficiency (%)	Emission coefficient (gCO_2/kWh)	
Coal, steam turbine	35	973	Pulverised coal, advanced steam	48	710	−263
Coal, steam turbine	35	973	Natural gas, combined cycle	50	404	−569
Fuel oil, steam turbine	35	796	Natural gas, combined cycle	50	404	−392
Diesel oil, generator set	33	808	Natural gas, combined cycle	50	404	−404
Natural gas, single cycle	32	631	Natural gas, combined cycle	50	404	−227

Source: Danish Energy Authority (2005).

and distribution levels. With a total of 13 projects in 2004, 2.8 million $MtCO_2$-eq of emissions was saved, as illustrated in Table 4. One viable way to achieve this is by installation of distributed generation at distribution networks of a power system.

6.3. Increasing the use of renewable energy

Distributed generation technologies have received a great deal of attention from the energy community due to a number of reasons. Some of these include their potential to save energy, increase the reliability of electricity supply, and decrease the cost of upgrading the existing electrical grid. Another reason for this growing activity is their benefits of low GHG emissions since they can use clean energy sources, other than fossil fuels. In 2008, about 19 percent of global final energy consumption came from renewables, with 13 percent coming from traditional biomass, mainly used for heating purposes, while hydroelectricity produced 3.2 percent. The rapidly growing new renewables, such as small hydro, modern biomass, wind, solar, geothermal, and biofuels accounted for the remaining 2.6 percent [5]. On a whole, the share of renewables in electric power generation is around 18 percent of global electricity, of which 15 percent came from hydroelectricity and 3 percent from new renewables [5]. Interestingly, scientists have advanced a plan to power 100 percent of the world‘s energy with wind, hydroelectric, and solar power by the year 2030, thus recommending renewable energy subsidies [53,54].

Renewable energy is the fastest-growing source of electricity generation in the IEO2010 reference case. Total generation from renewable resources increases by 3 percent annually, and the renewable share of world electricity generation grows to 23 percent in 2035 from 18 percent of 2007. Of this increase, about 80 percent is in hydroelectric power and wind power. The contribution of wind energy, in particular, has grown swiftly over the past decade, from 18 GW of net installed capacity at the end of 2000 to 159 GW at the end of 2009 [5,55]. Over the projection period, 2.4 trillion kWh is attributed to hydroelectric power and 1.2 trillion kWh to wind. These are 54 percent and 26 percent, respectively, of the 4.5 trillion kWh of new renewable generation added in the year.

Renewable power generators, whose percentage is growing annually, are spread across many countries, and wind power alone already provides a significant share of electricity in some areas. In this direction, nothing less than 83 countries have formulated some type of policy to promote renewable power generation, the commonest of which is feed-in-tariff policy [5]. The State of Iowa in the United States generates 14 percent of her power from wind, 40 percent in the northern German State of Schleswig-Holstein, and 20 percent in Denmark. A few of the countries that get most of their power from renewables include Iceland (100 percent), Brazil (85 percent), and Austria (62 percent). Others are New Zealand and Sweden with 65 percent and 54 percent, respectively, of their total power generation. In 2009, China alone added 37 GW of renewable power capacity, more than any other country in the world, to the total global renewables capacity [5]. Interestingly, scientists and industry experts have estimated that renewable energy sources, such as solar, can supply up to half of the world's energy demand in the next 50 years, even as energy needs continue to grow [56]. Further discussion of each of these renewables is given as follows.

6.3.1. Hydroelectricity

Hydroelectricity is the term referring to the production of electrical power through the use of the gravitational force of falling water. It is the most widely used form of renewable energy. Given its long history and large scale, hydropower is the most mature of the renewable industries. In 2006, 2998 TWh of hydroelectricity was supplied from the global installed capacity of 777 GW. This was equivalent to approximately 20 percent of the world's electricity, and accounted for about 88 percent of electricity from renewable energy sources. According to Ref. [5], hydropower has been growing annually by about 30 GW in recent years. Between 2008 and 2009, about 45 percent of the new renewable generating capacity of hydropower was added to the global capacity. This brought the global capacity from hydropower to 980 GW. Significant increases in hydropower capacity are in the project pipeline for 2011. When completed, the various hydro projects that are presently under construction in various countries are expected to increase the share of electric power worldwide by 4.5 percent.

Supportive policies of the government are responsible for the spurring growth of hydropower in Canada and the United States. For example, 10 GW of new capacity is proposed as a result of favourable policies, and the industry is reportedly planning to add up to 60 GW in coming years in the United States, mostly through repowering improvements and new technologies. Similarly, many utilities in Europe are upgrading existing facilities with more pumped storage under construction. On a global level, at least 15 pumped storage projects, which are under construction in 9 countries, are expected to add about 8.8 GW of new capacity. India expects to bring 400 MW of pumped storage capacity on line by 2012. Presently South African State owned utility, Eskom, is constructing a 1.35 GW pumped storage facility expected to be operational by 2013 [5].

Since hydroelectric dams do not burn fossil fuels, they do not directly produce CO_2. Hydro electric power plants produce a considerably lower output level of the CO_2 than fossil fuel powered

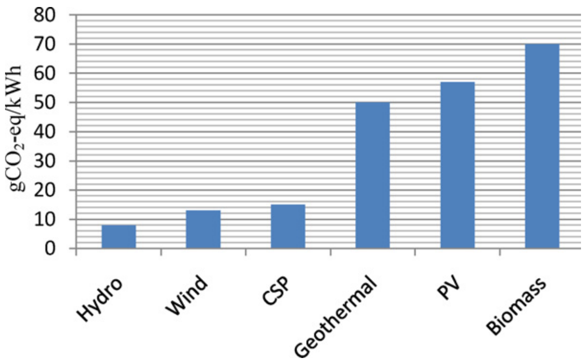


Fig. 12. Mean value of life-cycle GHG emissions for popular renewables.

energy plants. While some carbon dioxide is produced during manufacture and construction of the project, this is a tiny fraction of the operating emissions of equivalent fossil-fuel electricity generation. Overall, hydro-electric power's life-cycle GHG emissions range between approximately 1 and 34 gCO_2-eq/kWh, depending on whether it is run-off or reservoir type. It is suggested by IEA that hydropower could offset fossil-fuel power plants to give a mitigation potential of between 0.3 and 1.0 $GtCO_2$ per year by 2030, as presented in Table 2. The data used to plot Fig. 12 are obtained from Refs. [40,53,57], and presents the mean value life-cycle of selected renewable energy plants. From the figure, it is visible that hydropower has the least CO_2 emissions per unit of power produced.

6.3.2. *Wind power*

Wind energy is a high profile energy source that is currently enjoying strong political support in most countries, and its use is rapidly growing in many industrialised countries. Estimates of total wind power potentials in terrestrial facilities range from 20 to 50 trillion kWh [58]. Between 2004 and 2009, wind power capacity grew on the average of 27 percent annually. Among all the renewables, global wind power capacity increased the most in 2009. Despite the global economic crisis in the year, new wind power capacity installations reached a record high of 38 GW [5]. This capacity installed in the year is equivalent to nearly a quarter of total global installations, and cumulative capacity has doubled in less than 3 years. China was the top installer of wind power in 2009 with a capacity of 13.8 GW, representing more than one-third of the world market in the year. In both Europe and the United States, wind power accounted for 39 percent of all new electric generating capacity in 2009. By June 2010, another 16 GW of wind power was added, which brought the global total capacity to 175 GW [59].

Life-cycle GHG emissions from wind turbines are very site-specific and sensitive to wind velocity conditions. This is due to the cubic relationship of wind velocity to its output power. Wind power's life-cycle lie between 8 and 30 gCO_2-eq/kWh for on-shore, and 9–19 gCO_2-eq/kWh for off-shore turbines [40]. However, Fig. 12 shows the mean value of 13 gCO_2-eq per kWh of electricity produced from wind power, which is second lowest among the renewable energy sources sampled in the literature. Table 2 shows that 930 million $MtCO_2$-eq emissions would be avoided by 2030.

6.3.3. *Solar PV*

Between 2004 and 2009, grid-connected solar photovoltaic (PV) increased the fastest of all renewables technologies, with a 60 percent annual average growth rate for the 5-year period. Solar PV generates electricity in well over 100 countries and continues to be the fastest growing power generation technology in the world. At the end of 2009, the cumulative global PV installations surpassed 21 GW. This amount is 53 percent increase over that which was produced in 2008. Out of the total global capacity at the end of 2009, Germany alone produced a total of 9.8 GW, thus amounting to 47 percent of the existing global solar PV capacity [5]. This was followed by Spain and Japan whose total contributions in the year were, respectively, 16 and 13 percent of the total capacity. As of November 2010, the largest PV power plants in the world were located in Germany, Canada and Spain.

In terms of CO_2 emissions, PV generation produces less than 15 percent of the CO_2 a conventional coal-fired power plant would produce [56]. This small amount results from the production stage, as there are no CO_2 emissions during PV operation. A study has shown that a 2 kW photovoltaic system in Montana will avoid emissions of 0.68 lbs of NOx and 3643 lbs of CO_2, which is found to be equivalent to reducing CO_2 emissions equal to driving 4553 miles in an average passenger car. By so doing, it is possible to achieve a reduction in the CO_2 emissions equal to that absorbed by 1 acre of trees in 1 year. Further, a 9 percent reduction of CO_2 emissions was achieved using forecasted approach [60] when 800 MW capacity of wind generation – representing over 11 percent of the national installed capacity – was installed on Ireland power system. Solar PV's life-cycle GHG emissions are estimated to range from 43 to 73 gCO_2-eq per kWh of electricity produced [40], the mean value is, however, presented in Fig. 12, which shows a value of 57 gCO_2-eq/kWh.

6.3.4. *Concentrated solar thermal power (CSP)*

CSP is a technology by which sunlight is focused by mirrors or reflective lenses to heat a fluid in a collector at high temperature. The heated fluid, such as pressurised steam, synthetic oil, molten salt, flows from the collector to a heat engine where up to 30 percent of the heat is converted to electricity [53]. CSP emerged as a significant new power source during 2006–2010, after initial stalled development some two decades earlier. By early 2010, 700 MW of CSP was in operation globally, all in the U.S. Southwest and Spain. Of the global installations, the United States accounted for 65 percent. Construction and planning are under way for much more capacity in many other countries. For example, small plants and research projects are currently under way in France, Germany, Algeria, Egypt, and Morocco. Italy has a target of 200 MW to be online by 2012, while Abu Dhabi in the United Arab Emirates is planning a 100 MW commercial plant [5]. In early 2010, a deal of no less than 2 GW of CSP was signed by China to be completed by 2020, of which the first 92 MW was expected to commence in 2010.

The life-cycle emissions of CSP are estimated to range between 13.6 and 43 gCO_2-eq/kWh [57], of which the mean value of 15 gCO_2-eq/kWh is used for the plot of Fig. 12. However, Weisser [40] estimated CSP life-cycle as 8.5–11.3 gCO_2-eq/kWh. Solar PV and CSP combined together are estimated to avoid 250 million $MtCO_2$ in 2030, as illustrated in Table 2.

6.3.5. *Geothermal power*

The thermal energy generated and stored in the Earth is known as geothermal energy. It is energy extracted from hot water and steam below the Earth's surface. The difference in temperature between the core of the planet and its surface, known as geothermal gradient of 25–30 °C per kilometre of depth in most part of the world, is responsible for the continuous conduction of thermal energy in form of heat from the core to the surface. Geothermal energy has been harnessed for electricity generation; in addition to its historical uses for bathing and space heating. In 2010, the International Geothermal Association (IGA) reported that 10,715 megawatts (MW) of geothermal power in 24 countries was online, thus generating more than 67 TWh of electricity annually. This was expected to generate 67,246 GWh of electricity,

the amount of which represents a 20 percent increase in geothermal power online capacity since 2005. IGA projected this to grow to 18,500 MW by 2015, due to the large number of projects presently under consideration. In the same year (2010), the United States led the world in geothermal electricity production with 3086 MW of installed capacity from 77 power plants; followed by the Philippines, with her 1904 MW of capacity online. This amount is approximately 18 percent of the country's electricity generation [61]. The largest group of geothermal power plants in the world is located at the Geysers, a geothermal field in California.

Geothermal power is cost effective, reliable, sustainable, and environmentally friendly. The absolute values of GHG emissions for geothermal plants are between 15.1 and 55 gCO_2-eq per unit of electricity produced [53]. These emissions are much lower compared to those of the conventional fossil fuels plants [62]. Hence, geothermal power has the potential to help mitigate global warming if widely deployed in place of fossil fuels. Geothermal power average life-cycle is shown in Fig. 12, which is capable to avoid 0.43 $GtCO_2$-eq by 2030, as illustrated in Table 2.

6.3.6. Biomass power

Today, biomass can be understood as renewable energy source, derived from forestry, agricultural, and municipal residues as well as from a small share of crops grown specifically as fuel either for generation of electricity or production of heat. It is available in solid, such as straw or wood chips; liquid (e.g. vegetable oils and animal slurries that can be converted to biogas), and gaseous (biogas) forms. Some biomass can be converted to biofuels for transport. Currently, more than 50 countries around the world have adopted biomass power plants, which supply a growing share of electric energy. Recent increases in biomass use for power production have been seen in a number of countries around the world. In Europe, several countries are expanding their total share of power from biomass. Prominent among them are Austria, Finland, and Germany. Similarly, a few of several developing countries that have significant growth of biomass power include Brazil, Costa Rica, India, Mexico, Tanzania, Thailand, and Uruguay.

In 2008, over half of the electricity produced in the European Union from solid biomass was generated in Germany, Finland, and Sweden. As of the end of 2009, an estimated 54 GW of biomass power capacity was in place worldwide [5]. Biomass accounts for about 20 percent of Finland's electricity consumption, while Germany is Europe's top producer. Germany increased its generation of electricity with solid biomass 20-fold between 2002 and 2008, to 10 TWh, and had about 1.2 GW installed by the end of 2008. By early 2010, bioenergy accounted for 5.3 percent of Germany's electricity consumption, making it the country's second largest renewable generating source after wind power. In 2009, China's capacity rose to 3.2 GW, and the country plans to install up to 30 GW by 2020. On the other hand, India that generated 1.9 TWh of electric energy with solid biomass in 2008 had installed 835 MW of solid biomass capacity fueled by agricultural residues by the end of 2009.

Life-cycle GHG emissions for biomass systems vary substantially depending on the energy intensity of the fuel cycle, the bio-fuel properties, as well as the plant technology and its specific thermal conversion efficiency [40]. The range of life-cycle GHG emissions for biomass plants lies approximately between 35 and 99 gCO_2-eq per unit of electricity, most of which arise at the fuel-cycle stage. The mean value life-cycle emission is shown in Fig. 12. However, on the whole, biomass combustion is considered a carbon-free process because the resulting CO_2 from the fuel has previously been captured from the atmosphere by the plants being combusted [63]. Main barriers to widespread use of biomass for electric power generation include cost, low conversion efficiency and feedstock availability concerns.

6.4. Increasing nuclear power

The term nuclear renaissance, which simply means revival of nuclear power industry, has been the global talk in the energy supply circle since about a decade ago. The factors responsible for the renewed interest in the hitherto dormant nuclear industry include the increasing world energy demand, concerns over climate change due to emissions from combustion of fossil fuels, rising fossil fuel prices and new concerns about meeting GHG emissions limits [64,65]. In 2005, 2626 TWh of electricity, equivalent to 16 percent of the world's electricity, was generated from nuclear power. Today, nuclear energy is back on the policy agendas of many countries, with projections for new build similar to or even exceeding those of the early years of nuclear power. For example, China is currently embarking upon a huge increase in nuclear capacity of 70–80 GW by 2020, while India's target is to add 20–30 new reactors by the same time frame. There are also a considerable number of new reactors presently under construction in South Korea and Russia. In the United States, several dozen reactors are in various stages of proposal development. Meanwhile, World Nuclear Association (WNA) has projected nothing less than 1100 GW of nuclear capacity by 2060, and possibly up to 3500 GW, compared with the current base of 373 GW today [65].

Since many of the issues connected with nuclear power energy are global in nature, several initiatives have been taken to promote international cooperation and commerce in the field of nuclear science and technology. For example, communities in Finland and Sweden have accepted the local construction of permanent disposal sites for nuclear waste. France and Japan have set up joint government-industry schemes to help to build structures and systems to enable the establishment of civil nuclear programs in countries willing to develop them. In addition, these two countries are ready to draw on those countries' expertise to assist.

In terms of GHG emissions mitigation, the total life-cycle per kWh of electricity produced from new nuclear power plants are between 9 and 70 gCO_2-eq, with the lower number from an industry estimate and the upper value slightly above the average of 66 gCO_2-eq, from a review of 103 old and new life-cycle studies [53]. Fig. 11 shows the mean value life-cycle of 24.2 gCO_2-eq/kWh, which is very low compared to the conventional coal fired plants. Nuclear power is therefore an effective GHG emissions mitigation option, especially through license extensions of existing plants enabling investments in retrofitting and upgrading. Compared to a coal-fired power plant, nuclear power currently avoids approximately 2.2–2.6 $GtCO_2$ emissions annually or 1.5 $GtCO_2$ per year if the world average CO_2 emissions for electricity production in 2000 of 540 gCO_2/kWh is used [6]. However, various barriers to a nuclear renaissance have been identified. These concerns include unacceptability by many countries, unfavourable economics compared to other sources of energy, its unsafe nature, and its association with weapons production.

6.5. Decarbonising fossil fuels

Burning of fossil fuels, particularly coal is no doubt a major source of anthropogenic CO_2 emissions, due to the carbon intensity. The GHG emissions in the atmosphere could be reduced from power industry on a national level by decarbonising the primary energy sources, particularly fossil fuels [66]. This option could be achieved in several ways as discussed in this section.

6.5.1. Switching to low-carbon fossil fuels

The amount of CO_2 emitted into the atmosphere depends on the amount of carbon content of the fossil fuels burnt for energy production. Reducing the carbon content of the energy source could be achieved by replacing fuels with relatively high CO_2 emissions

such as coal, especially lignite; with those of lower CO_2 emissions such as natural gas can lead to significant GHG emissions savings. The average life-cycle GHG emissions from lignite/coal-fired plants are approximately equal to two times that of gas-fired plants [40]. Examples of supply-side fuel switching strategies include using combined-cycle, natural-gas-based power plants in place of coal plants. Fuel switching from bituminous coal to natural gas has a potential to reduce CO_2 emissions by approximately 43 percent of the energy consumed [52]. Likewise, switching from oil to natural gas would achieve the same result, though at a lesser capacity. Table 3 is presented to illustrate the emissions benefits that could be derived from fuel switching and plant efficiency improvement. It could be seen that by replacing a natural gas single-cycle turbine with a combined cycle (CCGT) of similar output capacity, it is possible to reduce CO_2 emissions per unit of output by around 36 percent.

In 2004, a total of 51 fuel switching projects were reported. This is equivalent to CO_2 emissions reduction of 12 million $MtCO_2$-eq (11.8 million $MtCO_2$-eq from direct sources and 0.2 million $MtCO_2$-eq from indirect sources) recorded in the year, as shown in Table 4. However, apart from the fact that switching from coal to gas on a substantial scale could result in increase in the price of gas, thus eroding the economic benefit of gas, this option also requires further investment to develop a supportive infrastructure that could facilitate fuel switching. These limiting factors could be overcome when regulatory or investment incentives are provided by the government.

6.5.2. *Plant availability improvements*

Reducing the frequency as well as the length of planned and unplanned power plant outages could result in increased use of a power plant. Emissions reduction is attained when generation from lower carbon emitting plants displaces generation from a higher carbon emitting plants. For example, a large load-based plant such as nuclear plant can result in appreciable reduction in CO_2 emissions with a fairly small improvement in its plant availability. According to a United State electric utility (Southern Company), 1.786 TWh of its generation, which could have come from fossil fuels was instead generated from nuclear power in 2004, after its Vogtle plant availability improvement. By so doing the company was able to successfully reduce its GHG emissions by 1.7 million $MtCO_2$-eq in that year [52].

Several major efforts have been made in recent years in improving the performance and reducing the length of scheduled refuelling outages of nuclear power plants. Some of the factors which have yielded positive results in shortening the outage durations in nuclear plants include online plant maintenance, optimum scheduling, and use of robotic inspection equipment for steam generator and reactor inspection activities, which altogether contribute to plant availability. A total of 45 availability improvement projects were carried out in data year 2004, out of which 34 involved nuclear power plants. These projects led to a reduction of 86.6 million $MtCO_2$-eq and 7.2 million $MtCO_2$-eq from direct and indirect sources, respectively [52], as shown in Table 4.

6.5.3. *Increasing lower carbon-emitting capacity*

A power supplier could reduce or avoid reliance on higher emitting plants, thus reducing the net GHG emissions from all plants, by increasing the capacity of the existing generating units, which produce relatively low CO_2 emissions. For example the capacity of an existing hydroelectric plant could be increased or a new low-emitting power plant could be constructed, where such has not being in existence, at the expense of a higher carbon emitting plant. One hundred projects on increases in low- or zero-carbon emitting capacity was reported in 2004. Of this, emission reductions from low-emitting carbon capacity projects amounted to a reduction in GHG emissions of 72.7 million $MtCO_2$-eq from both direct and indirect sources in the year [52] (see Table 4).

7. Conclusion

Global warming, described as a serious environmental threat, is caused by greenhouse gases that trap heat in the atmosphere. These gases are majorly emitted in the air as a result of human activities, which include fossil fuel burning, land-use change, population growth, etc. Globally, the power sector is responsible for the largest share of present day GHG emissions, particularly CO_2. In 2008, energy supply sector, which comprises of power and heat generation, contributed 41 percent while transport, next to it, contributed 22 percent of the total global CO_2 emissions. The reference scenario of the IEA's 2006 World Energy Outlook projected that power generation will contribute to 50 percent of the increase in global CO_2 emissions between 2004 and 2030. Therefore, mitigation strategies that can effectively reduce GHG emissions from electricity generation may play a pivotal role in meeting countries' obligations under the Kyoto Protocol and UNFCCC.

While there are technology winners with regard to life-cycle GHG emissions in electricity generation, this paper has shown that renewable energy technologies and nuclear power have lower life-cycle GHG emissions than fossil fuel technologies. In this direction, renewable energy sources are expected to become increasingly important for our future energy demand. However, since renewables and nuclear energy may not be available at sufficient quantities at competitive prices or not acceptable on social or political grounds, the immediate energy demand is likely to be met by conventional fossil fuel combustion, a trend observed into the foreseeable future. In this regard, carbon capture and storage technology becomes a viable option to severely reduce the amount of GHG emissions. Fortunately, this option has been confirmed to be very effective, which could cut about 90 percent of GHG emissions from the conventional power plants.

Other possible mitigation techniques as discussed in this literature include decarbonisation of fossil fuels, adoption of a more efficient fossil fuels conversion, energy efficiency improvement, and rehabilitation of the existing power plant for higher efficiency. On a whole, the information presented in this paper will help power generation companies realise the magnitude of the damage their power plants do to the environment, and hence enable them know the appropriate areas to address the GHGs emissions issues, to prevent further deterioration to the environment.

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